The Milky Way

Lecture 15
March 19, 2020

Monument Valley, Utah


Chilean Andes

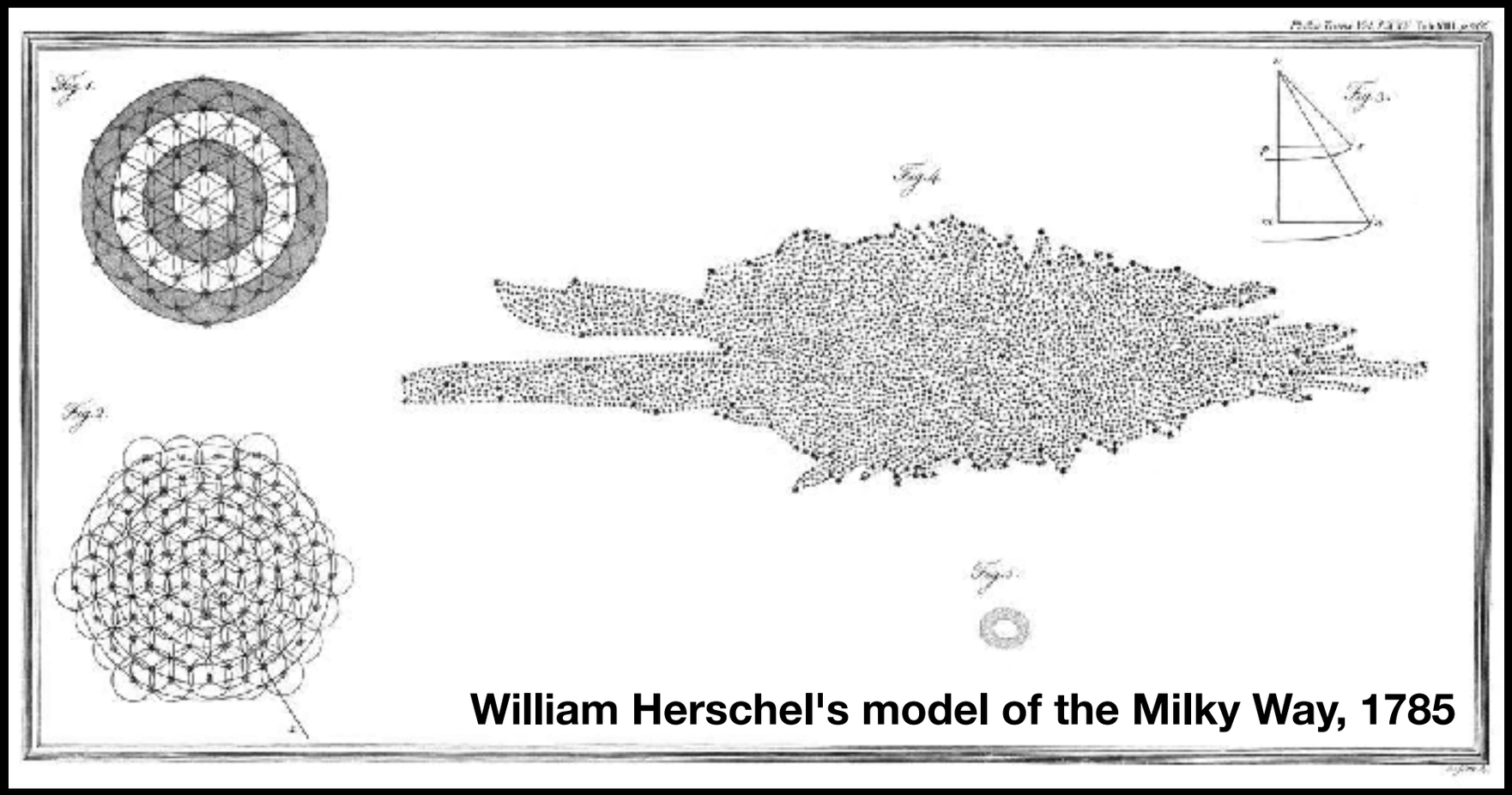
The Milky Way

- The Western name for the Milky Way is a direct translation of the ancient latin, “via lactea”.
- The word galaxy derives from the ancient greek, γαλαξίας (galaxias) meaning “milky”.
- To the naked eye, the Milky Way appears as a band of unresolved stars in the night sky.
- Galileo, in 1610, observed the Milky Way with a telescope and first resolved the splotchy band into individual stars.
- Up until the 20th century people did not appreciate how large the Milky Way was (until the 1920s, it was thought to be a hundred lightyears across with the Sun at the center).

Herschel's Universe

- William Herschel made many contributions to astronomy in the late 18th century:
  - among these, Herschel and his sister Caroline discovered more than 2,500 new nebulae, most of which are planetary nebulae, but some of which we now know to be distinct galaxies
  - Herschel discovered Uranus, two of its moons, and two of Saturn's moons
- Herschel assessed the size and shape of the Milky Way by noting that if you looked in certain directions you could see more stars.
- Herschel concluded that the Universe must be "deeper" in these directions.

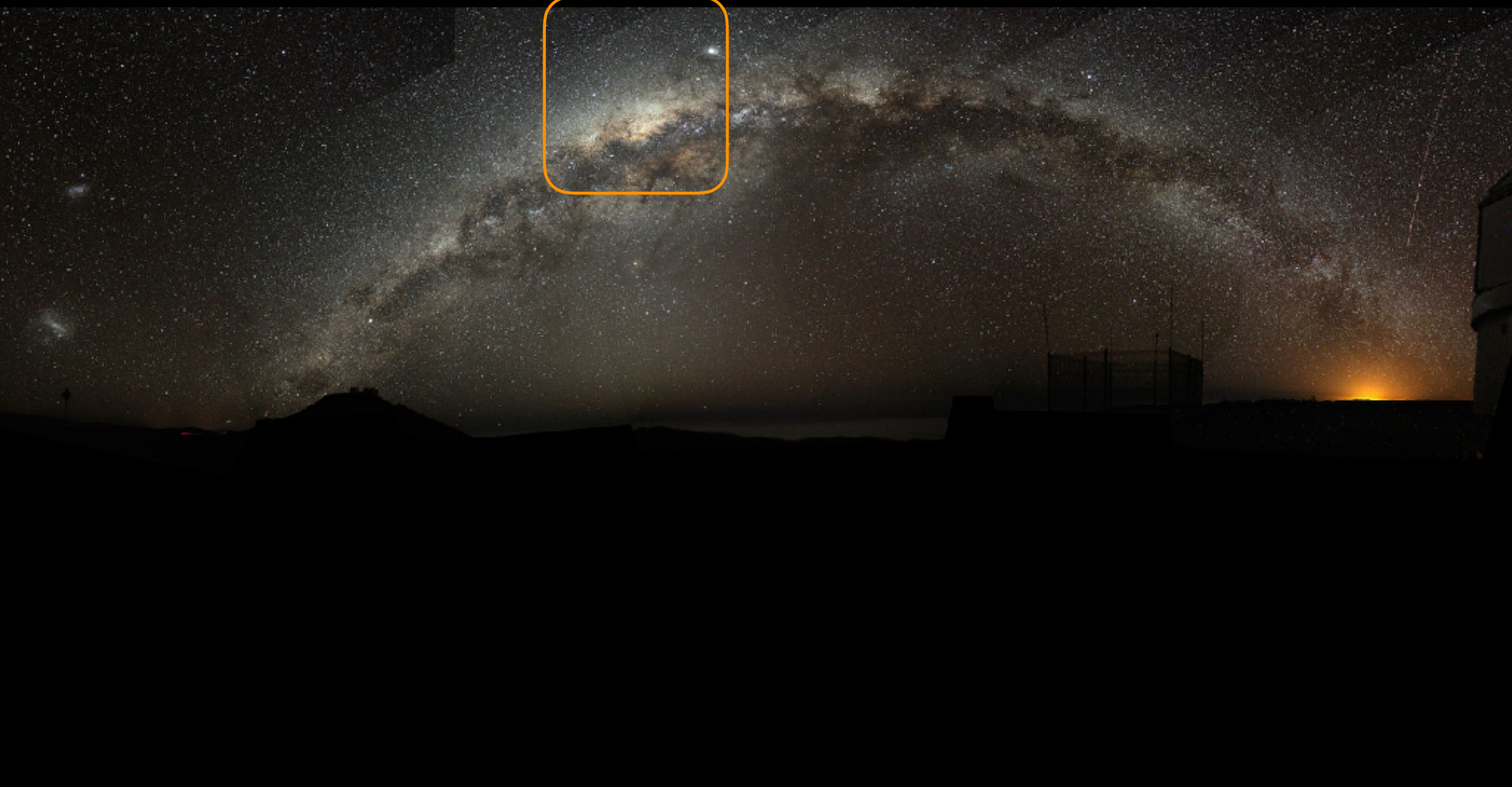
Hershcel's Universe



William Herschel's model of the Milky Way, 1785

- Assumptions:
  - all stars have approximately the same absolute magnitude
  - the number density of stars within the Milky Way is approximately constant
  - There is no obscuring material in the Milky Way
- Concluded:
  - Milky Way is flattened disk
  - The Sun is near the center
  - However, he left the absolute size unspecified

Sagittarius constellation



Kapteyn's Universe

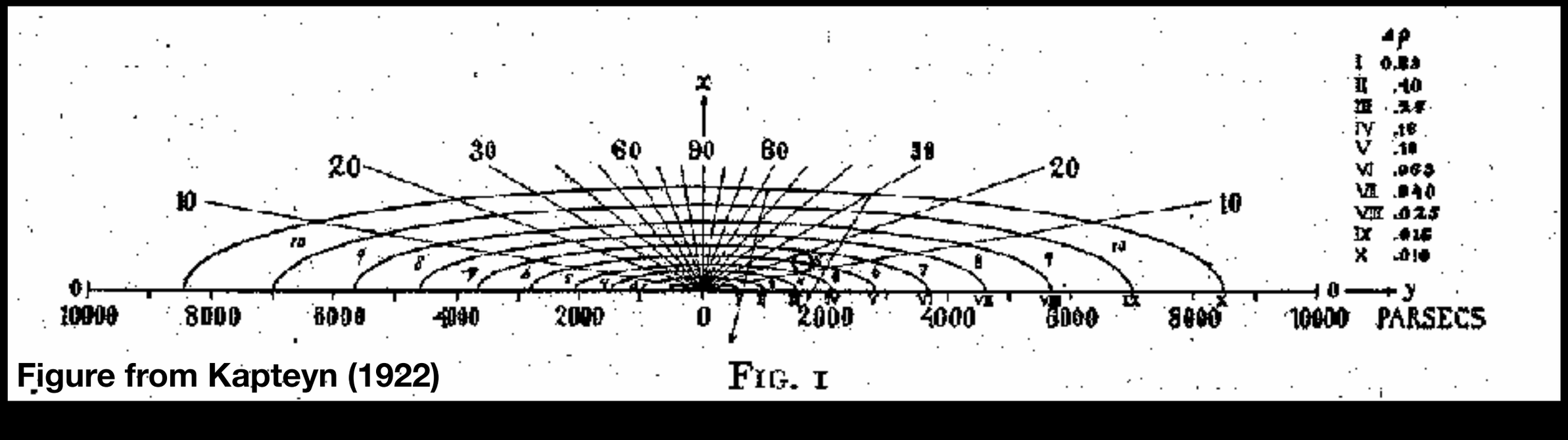


Figure from Kapteyn (1922)

FIG. 1

- Early in the twentieth century a Dutch astronomer, Jacobus Kapteyn, undertook a more detailed program of star counting.
- Kapteyn suspected that interstellar absorption was present and predicted that it would give rise to "reddening", but he estimated it to be small and ignored this effect in his model.
- Kapteyn found:
  - the Universe was a disk-like "oblate ellipsoid" with a height of 2000 pc and a width of about 8000 pc.
  - the stellar density decreases from center to the edges
  - the Sun is 650 pc from the center

Shapley's Universe

- **Harlow Shapley of the Harvard College Observatory examined the distribution of Globular Clusters in the "Universe".**
- **Globular Clusters are not confined to the disk as most stars are, they are found at positions significantly away from the stars of the disk**
- **There is a marked increase in the number of GCs found near the brightest portion of the Milky Way disk (towards Sagittarius)**
- **He found that the distribution of globular clusters is centered 15,000 parsecs from the Sun and has a size of ~ 55,000 parsecs**

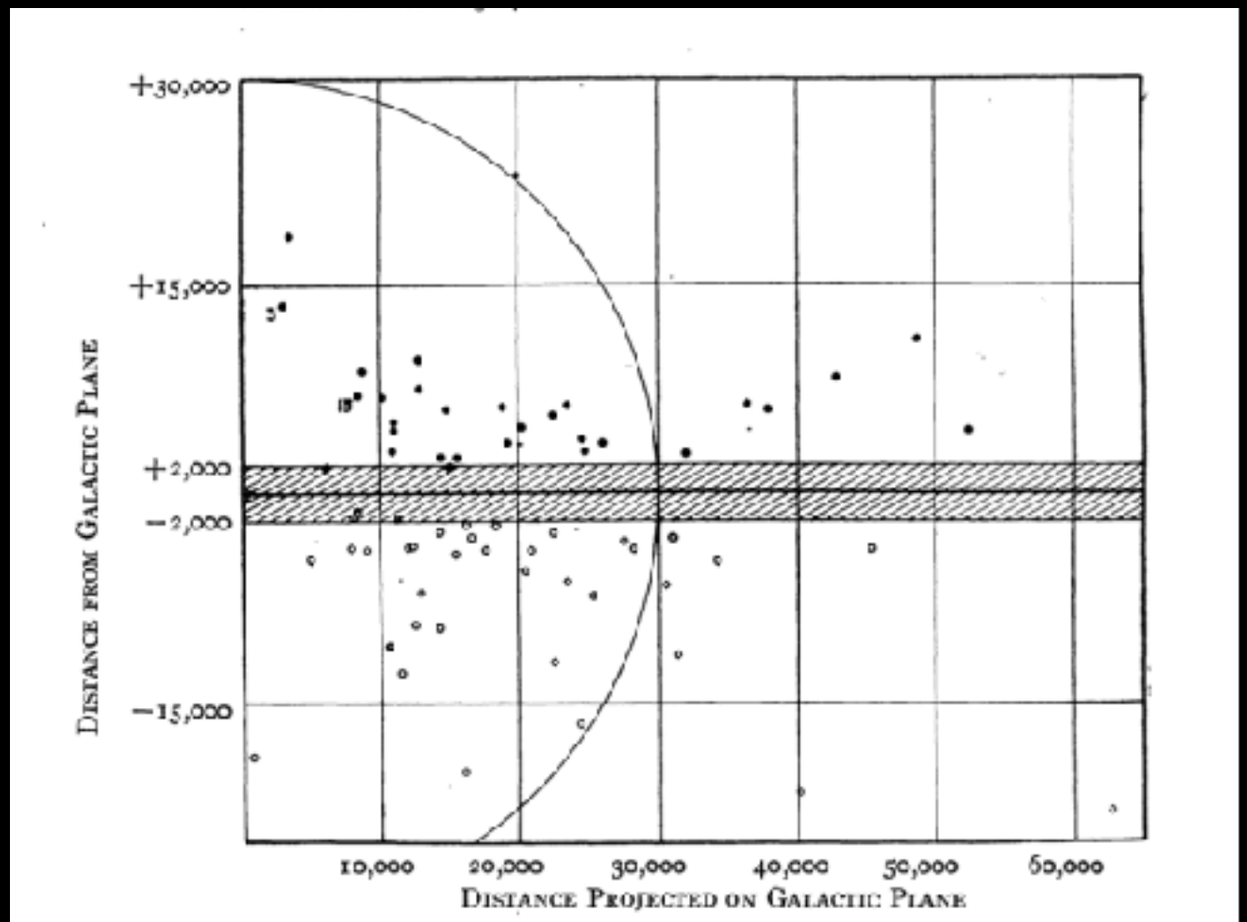
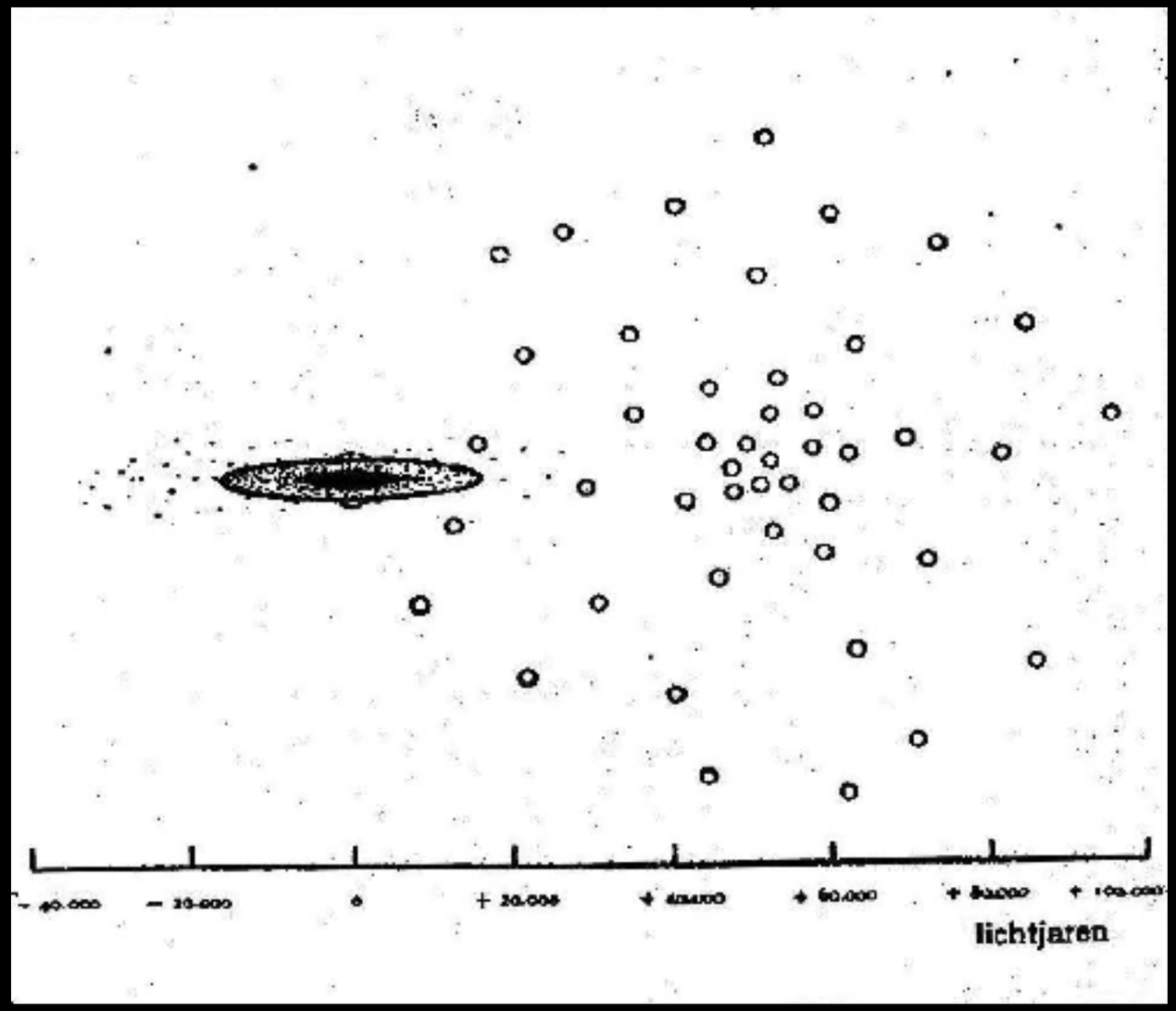


Fig. 28. Distribution of globular clusters, illustrating the segment of avoidance. The unit of distance is one parsec. The small semi-circle, with radius corresponding to a parallax of 0".002, illustrates the region around the Sun that contains all but a few of the stars in Charlier's B-type cluster. The large semi-circle shows the distance to which the present results are thought to be complete. N. G. C. 4147, with co-ordinates 10,500 and +51,400, is not on the diagram. The well-known clusters, Messier 3 and Messier 13, are indicated by numbers.

Shapley's vs Kapteyn's Universe

- **Shapley's Galaxy/Universe was nearly 10 times bigger than Kapteyn's!**
- **Shapley found it inconceivable that the Universe could be much bigger**
- **Shapley supposed that the Milky Way was the entire Universe and that the "spiral nebulae", like Andromeda, were wisps within the Milky Way**
- **Kapteyn and others thought that the Galaxy was small, but that the other nebulae were themselves galaxies similar to ours**



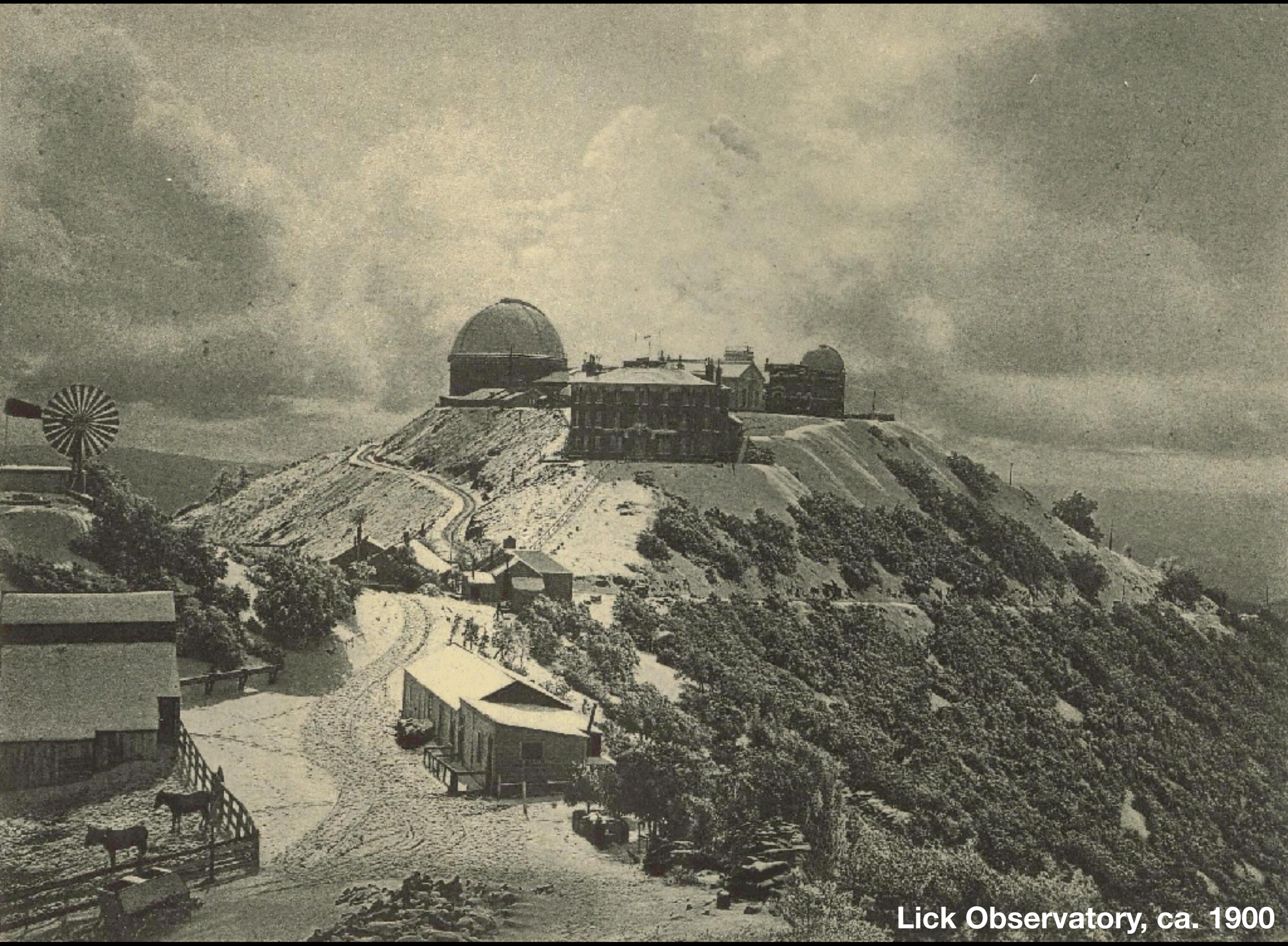
Comparison of Kapteyn's (left) and Shapley's (right) Models of the Milky Way. Figure Credited to Jan Oort.

The Spiral Nebula

- Initially, the “Galaxy” and the “Universe” were used more or less synonymously
- In the eighteenth century Immanuel Kant suggested that many “nebulae” that are seen in the sky may actually be “island universes” similar to the Milky Way itself
- In the 19th century Lord Rosse performed astronomical studies and discovered the spiral nature of some nebulae, today known to be spiral galaxies
- At the start of the 20th century it was not at all clear what the spiral nebulae were

Lord Rosse’s drawing of M51

Leviathan of Parsonstown



Lick Observatory, ca. 1900

M51, Lick Observatory, ca. 1912

The Great Debate

- This dichotomy set the stage for the “Great Debate”, which occurred at the National Academy in Washington, D.C. in April 1920
- Harlow Shapley spoke and advocated a big galaxy containing the spiral nebulae
- Heber Curtis (well-known astronomer and former Allegheny Observatory director) spoke, advocating for a smaller Galaxy, and that the nebulae were distant galaxies or “island universes” unto themselves

M51, Lick Observatory, ca. 1912

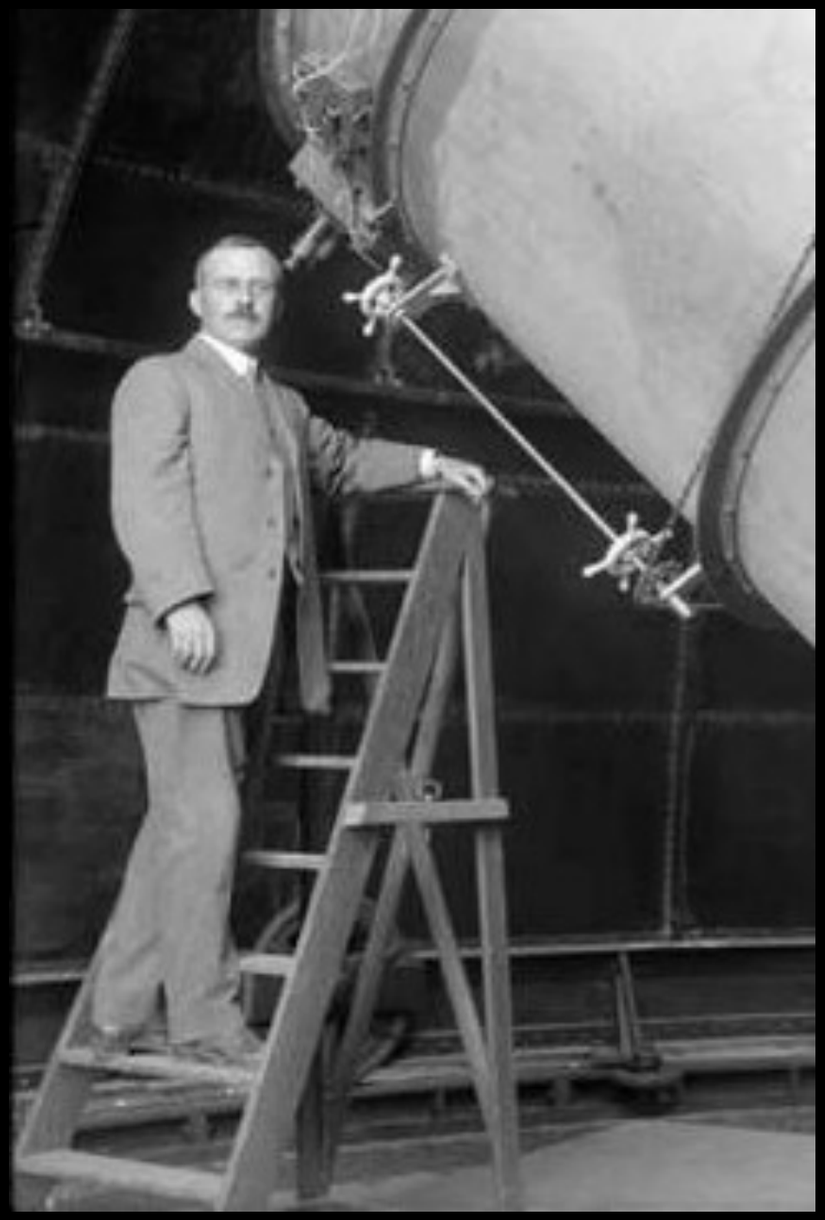
Shapley's Argument

- **The Galaxy was inconceivably large, and to suppose our galaxy could be a building block of something much larger seemed preposterous**
- **The nebulae appear different from the Milky Way: the nebulae are generally bluer than the Milky Way.**

Harlow Shapely

Curtis's Argument

- **If the stars in Globular Clusters are as bright as typical stars in the Milky Way, they cannot be as far away as Shapley claimed**
- **Bright novae are seen regularly in the Andromeda galaxy indicating that there must be a large number of stars there! It cannot just be a nearby wisp of gas and stars.**

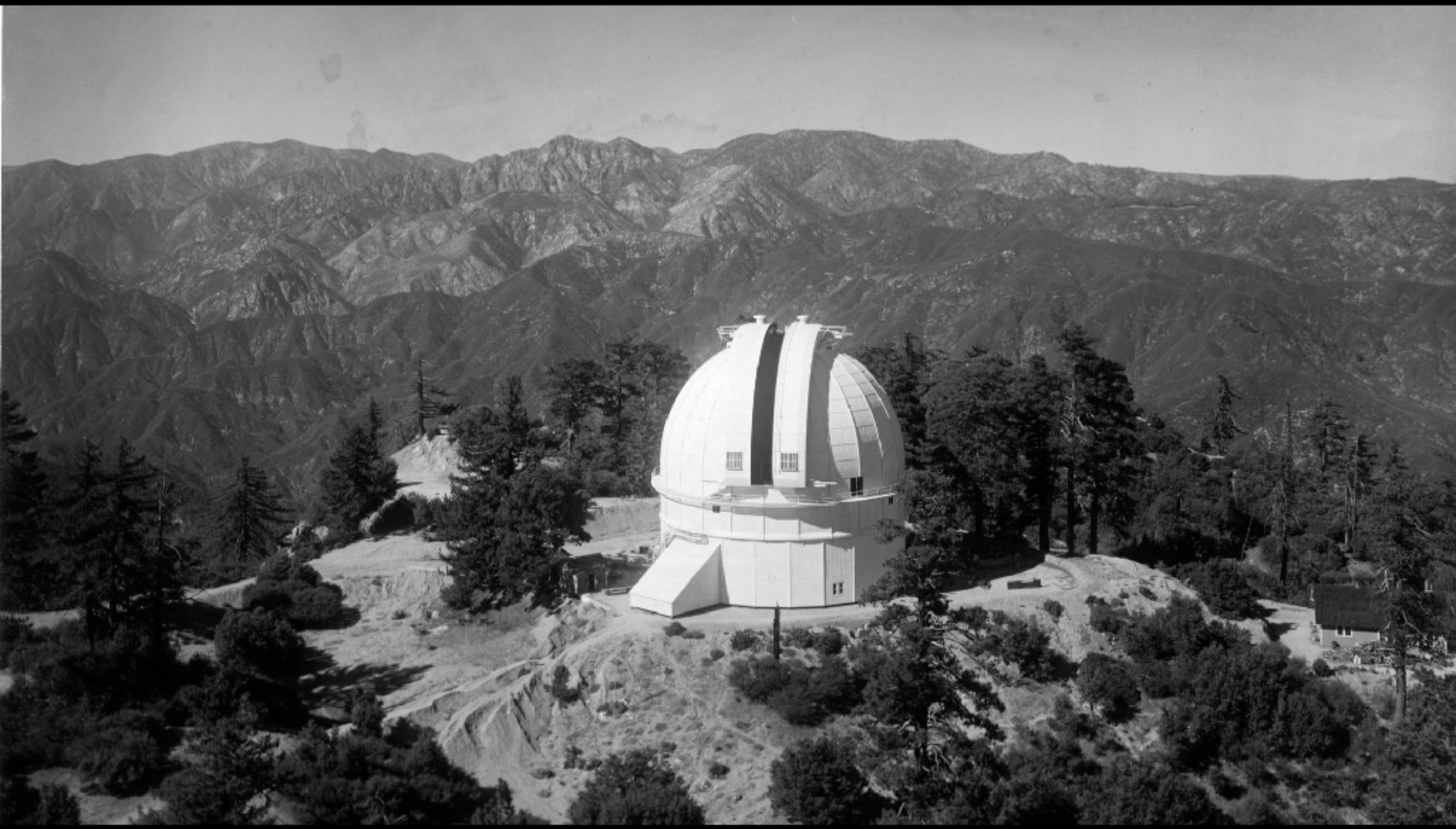


Herber Curtis

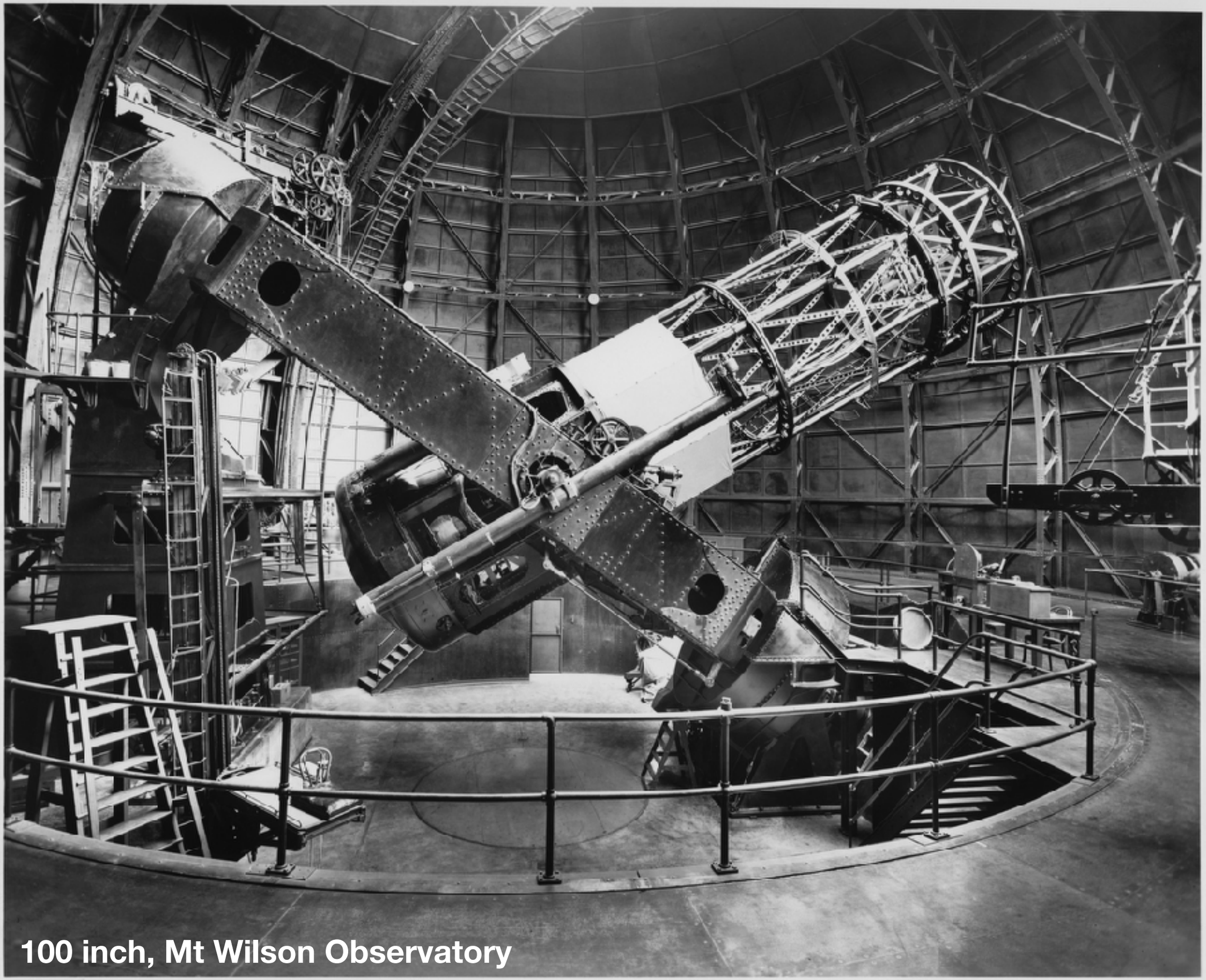
The Resolution

- **Edwin Hubble eventually resolved the debate only five years later.**
- **He made use of the new 100-inch telescope on Mount Wilson.**
- **He used cepheid variable stars as a tool to estimate distance.**
- **First, Hubble used the new telescope to resolve individual stars in the nearby nebula Andromeda for the first time, indicating that Andromeda was an independent galaxy.**
- **He used cepheids to place Andromeda at a distance of 300,000 parsecs!**

Edwin Hubble



Mt. Wilson Observatory, 1916

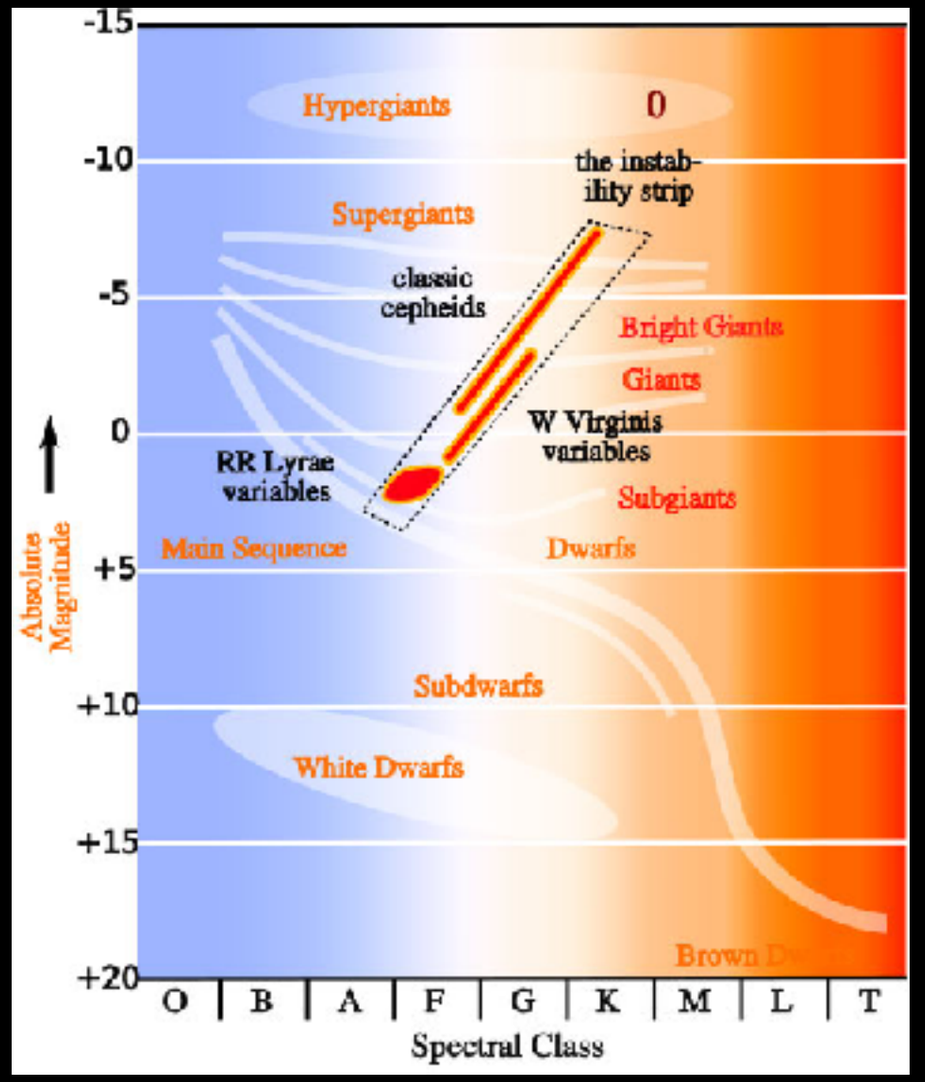


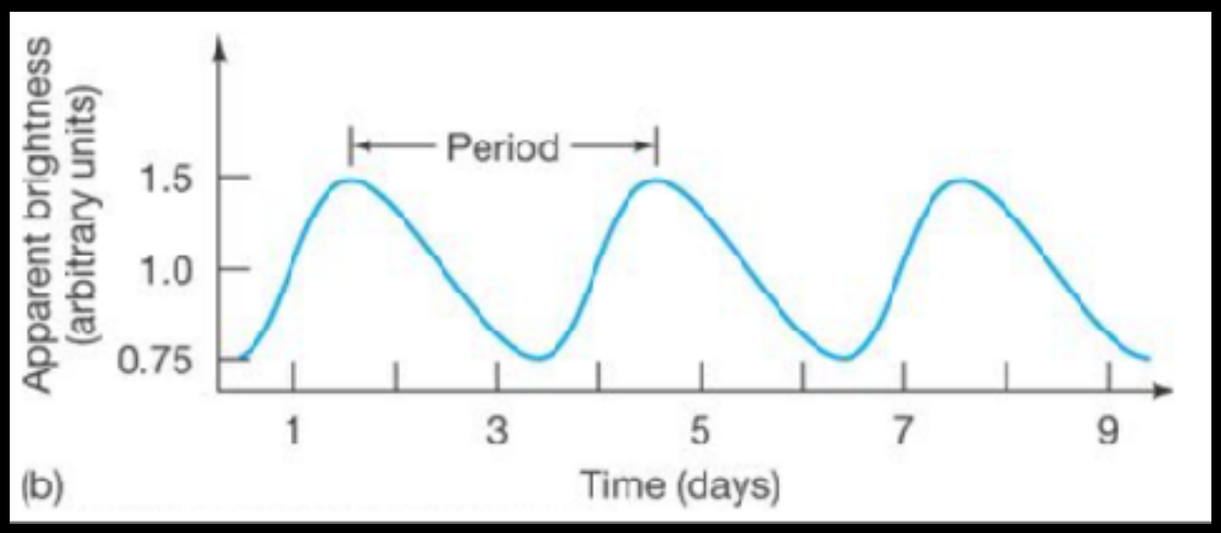
100 inch, Mt Wilson Observatory

M31, Hooker 100 inch

Cepheid Variable Stars

- **Cepheids are the most luminous variable stars in the instability strip on the H-R Diagram.**
- **Cepheids are extremely luminous, so they can be seen in very distant galaxies.**
- **Cepheids have a unique "sawtooth light-curve" that makes them relatively easy to identify, even at great distances.**
- **Cepheids follow a known period-luminosity relation that had been calibrated locally.**
- **At visible wavelengths, Cepheid luminosity scales roughly with period.**





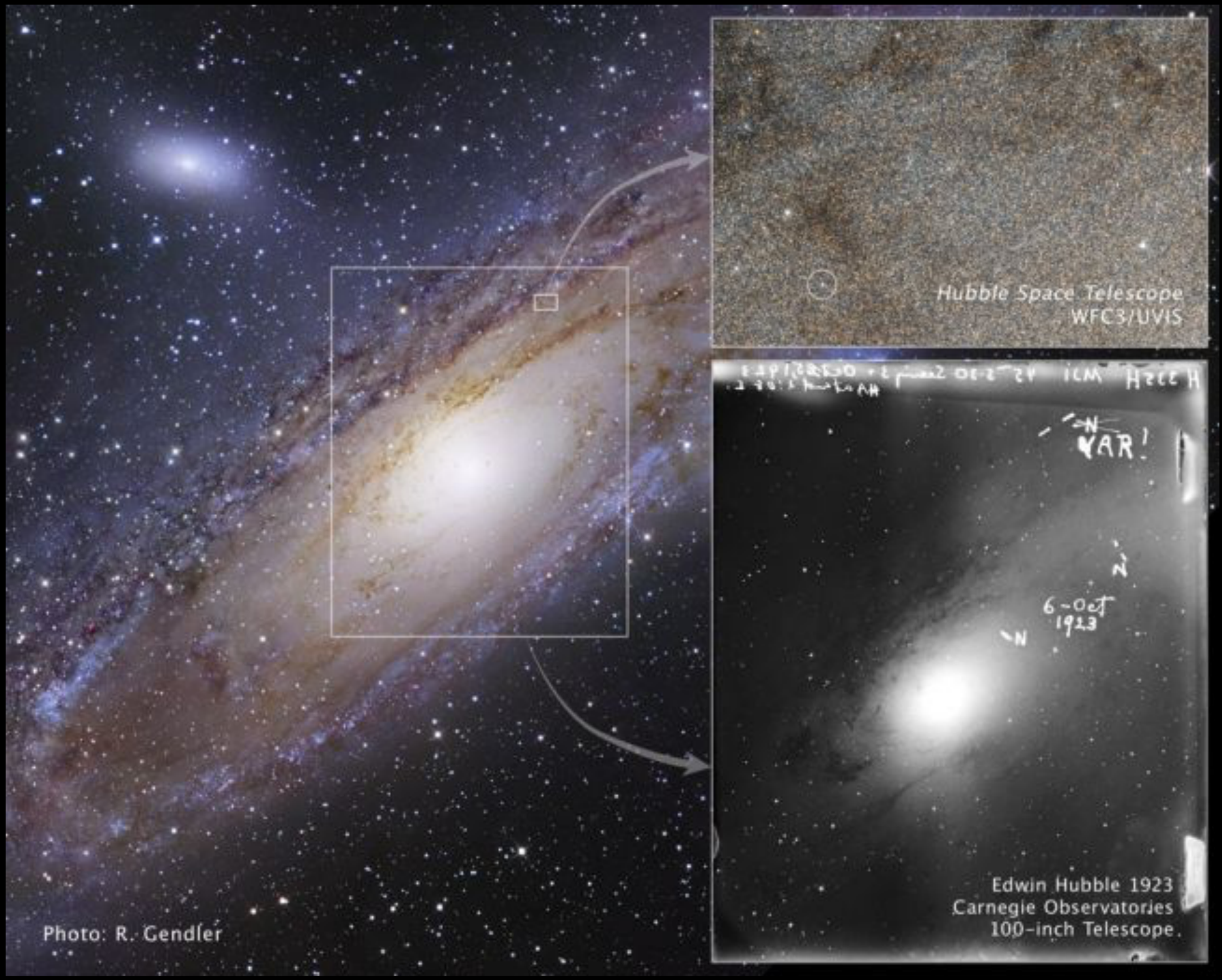
cepheid period-luminosity relation

$$\frac{L}{L_\odot} \simeq 335 \left(\frac{P}{1 \text{ day}} \right)$$

H 331 H W31 Oct 1853 H0 - 2·30

VAR!

6-Oct
1923


Hubble Space Telescope
WFC3/UVIS
VAR!
6-Oct
1923
Edwin Hubble 1923
Carnegie Observatories
100-inch Telescope.
Photo: R. Gendler

Cepheid Variable Star V1 in M31
HST WFC3/UVIS

F475X
F600LP

5″

N
E

Dec. 17, 2010

Dec. 21, 2010

Dec. 30, 2010

Jan. 26, 2011

Why the Confusion?

- None of these scientists appreciated the influence of interstellar dust
  - Interstellar dust is found mostly in the Galaxy's disk, just as stars
  - Interstellar dust absorbs photons and scatters photons (via a special bound-bound scattering process called Rayleigh scattering)
  - Dust absorbs light, that is in fact why we see the dark "dust lane" that runs through the Milky Way
    - We now know that "dust lanes" are evident in the disks of many galaxies that we happen to see from their edge
    - The Milky Way's dust, made stars near the center of the galaxy difficult or impossible to see at the time
- The Sun is actually part of a pocket of stars that is more densely packed than average called Gould's Belt
- Both of these facts made it appear as though most stars were located near the Sun, leading to errors in Kapteyn's model.

Why the Confusion?

- What about Shapley's claim that the "nebulae" are bluer than our Galaxy?
- Rayleigh scattering of short-wavelength (blue) light is much more efficiently scattered than long-wavelength (red) light
- If we look through the edge of a galaxy, its stars appear redder because blue light is more efficiently scattered away!
- We see most nebula from other vantage points, where dust is less prominent, so we see more of the true, bluer colors of these stars

The Interstellar Medium

- **The diffuse material that is found in the space between stars is called the Interstellar Medium (ISM).**
- **The composition of the ISM is largely similar to that of the Sun:**
  - **71% Hydrogen and 27% Helium by mass,**
  - **trace amounts of Iron, Oxygen, Carbon, Nitrogen, Silicon, and a few other elements**
- **The ISM is remarkably diffuse :**
  - **Typical densities are billions of times more diffuse than can be achieved with terrestrial vacuum pumps.**
- **Nearly 1% of the ISM is in the form of what astronomers refer to as “dust”**
- **Iron, Silicon, Carbon, and other heavy elements are ejected from stars and when they get to cooler regions, they prefer to stick together in small clumps.**
- **This is what astronomers refer to as dust, but it is more appropriately the “soot” from nuclear burning in stars.**

Interstellar Medium

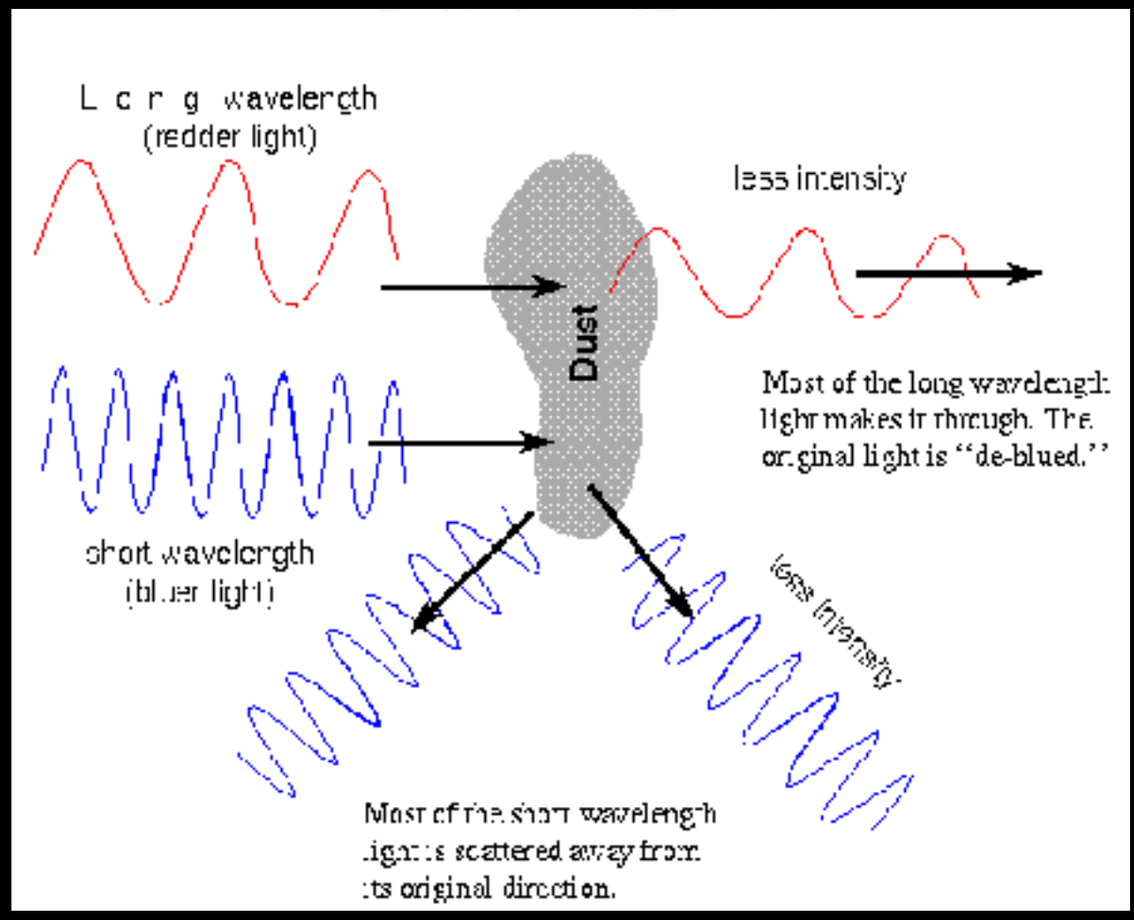
towards Milky Way center

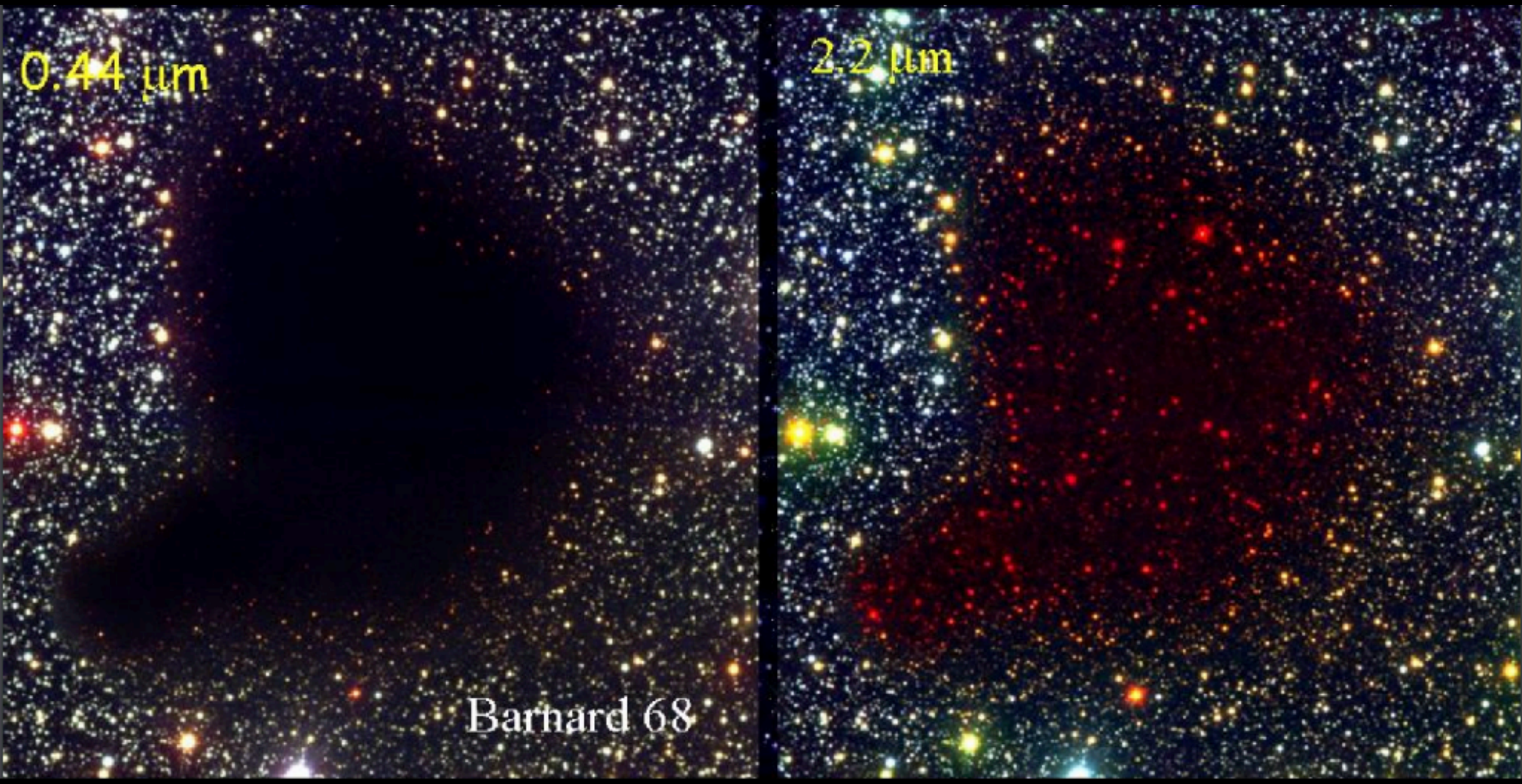
Barnard 68

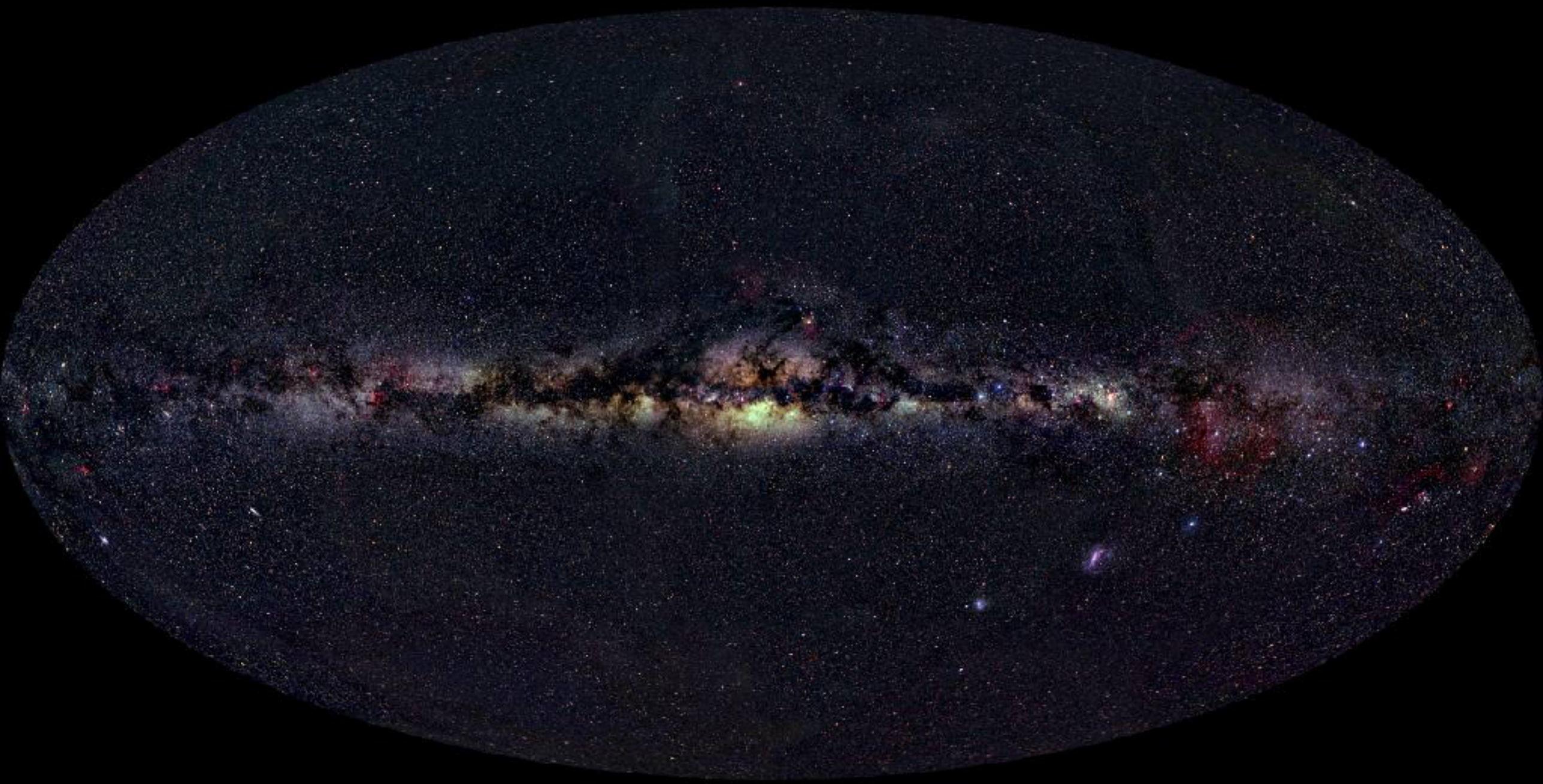
- The dustiness of the ISM makes it very hard to see through.
- Blocking light from objects at large distances by dust is referred to as interstellar extinction by astronomers.
- There are many prominent examples of extinction by dust blocking our views of distant objects.
- Accounting for extinction is a common problem in astronomy.

Reddening and Extinction

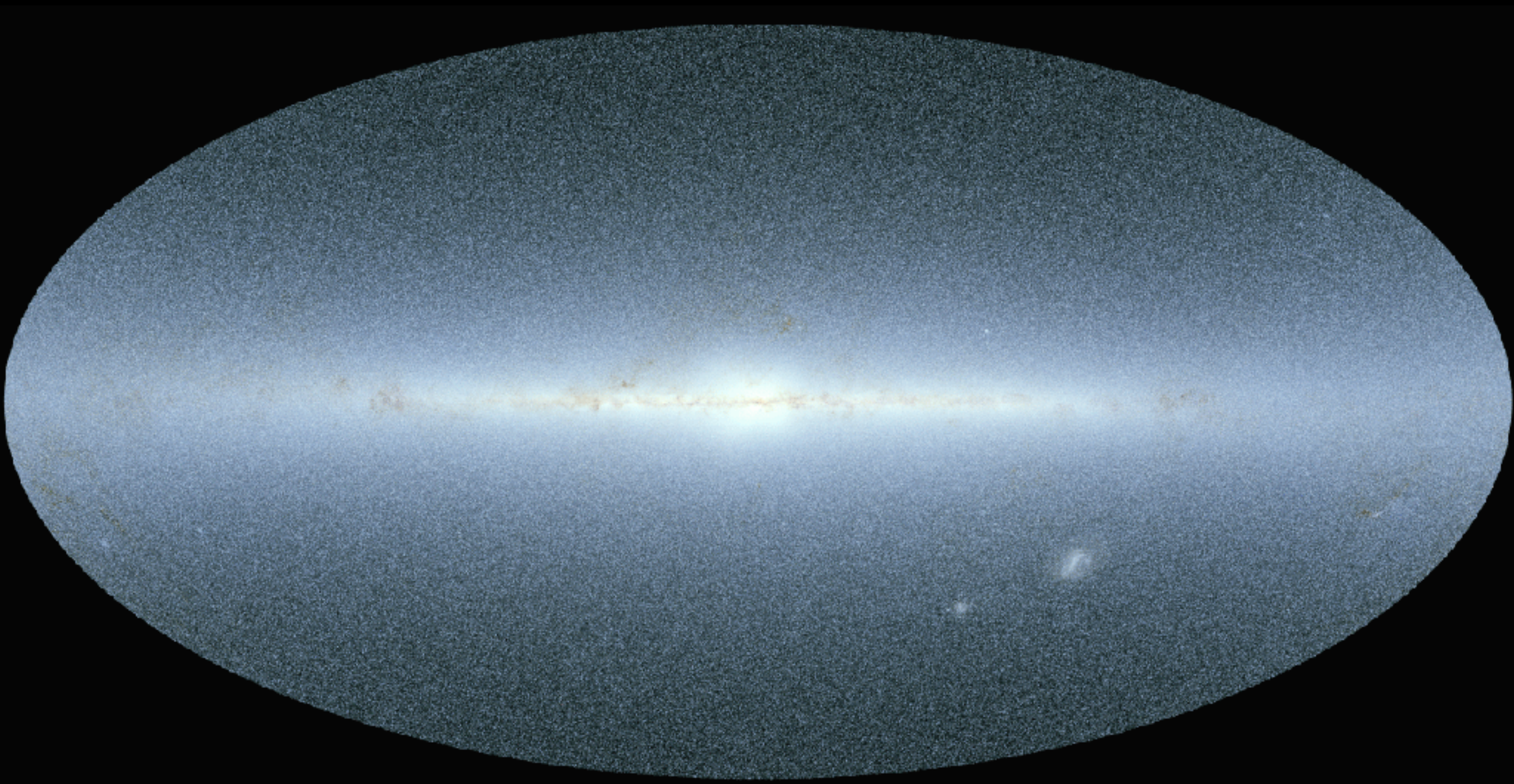
- **Rayleigh Scattering**
  - **Light interacts and scatters strongly off of molecules/atoms that are close to or larger than its wavelength**
  - **Scattering is much less important when the wavelength of the light is much longer than the typical size of the object**
    - **Dust has sizes typically near ~100 nm in length**
- **Interstellar dust grains often are as large as several hundreds of nanometers (~100 nm) across but seldom much larger.**
- **Since blue light has a shorter wavelength than redder light, blue light is preferentially scattered causing things to look redder.**
- **Longer wavelengths, like the infrared (IR), are much less susceptible to dust: we see through dust in the IR**




0.44 μm
2.2 μm
Barnard 68

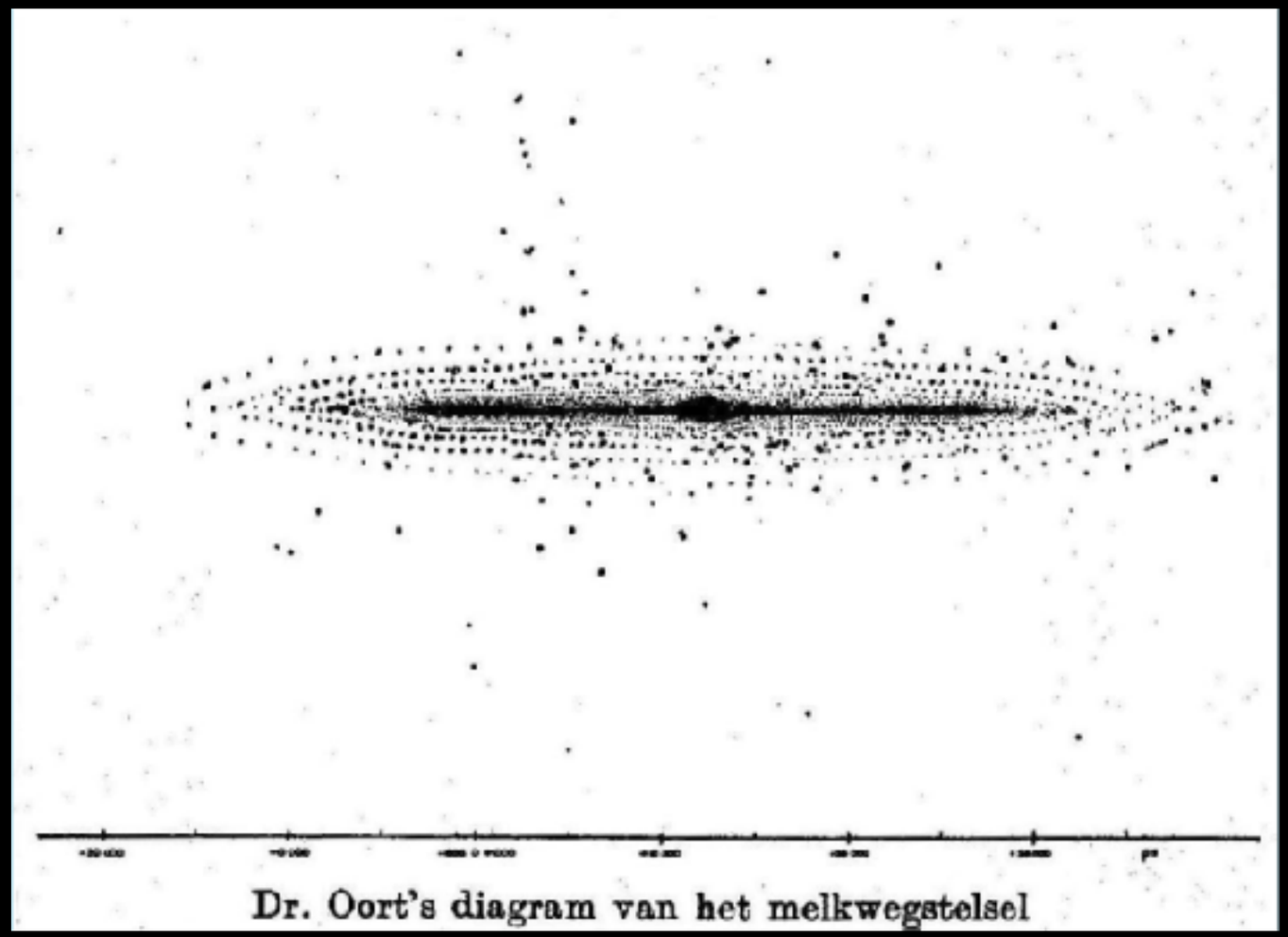


Visible Light



Infrared Light (Two Micron All-Sky Survey)

Reconciling



Dr. Oort's diagram van het melkwegstelsel

- Astronomers like Jan Oort reconciled the two models and observations by accounting for this absorption.
- Accounting for absorption increases the inferred size of the disk.
- Accounting for absorption changes the distance calibration used for the globular clusters (variable star period-luminosity relations).
- Finally, the Milky Way's globular Cluster system is intrinsically larger than the stellar disk

The Final Nail

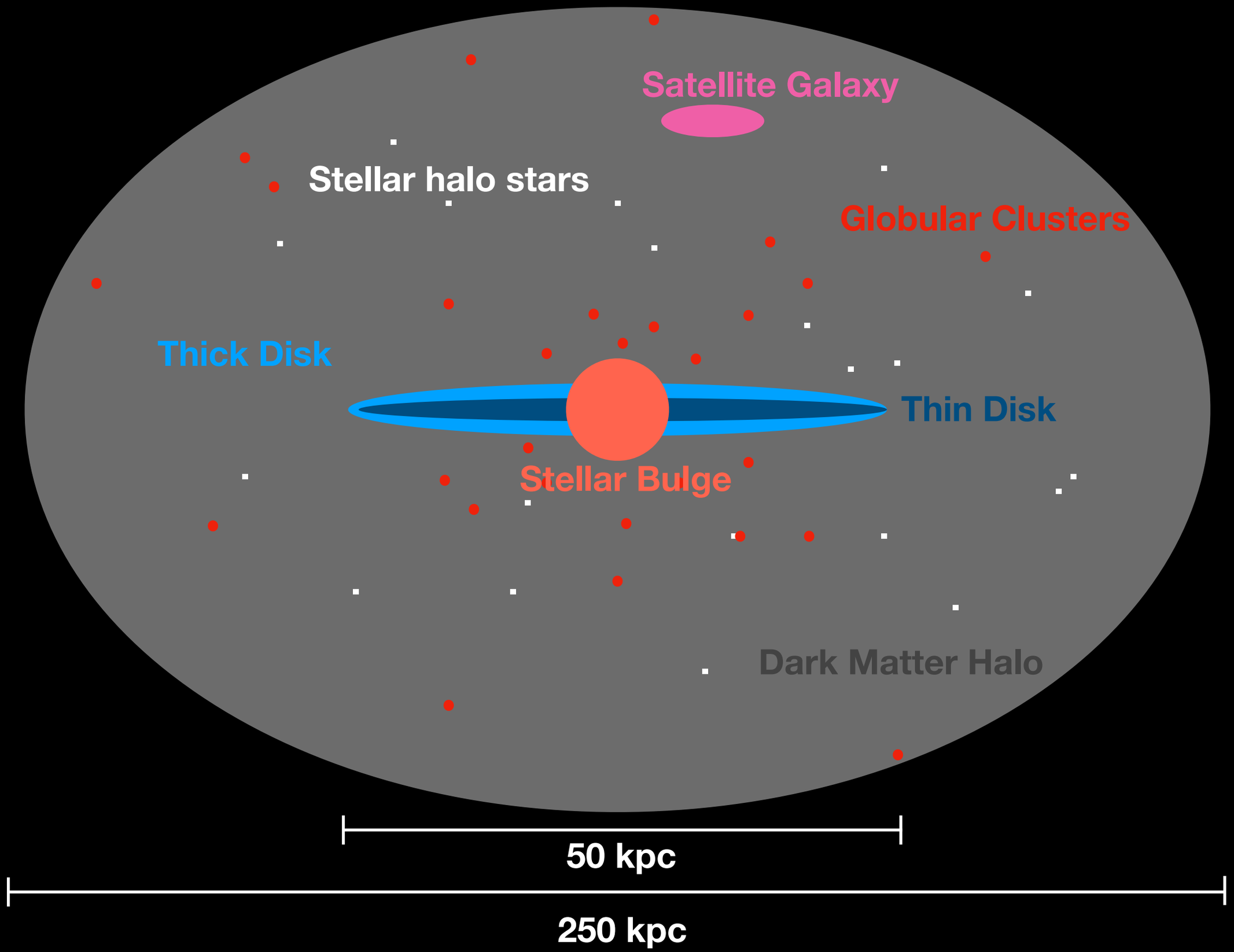
- **Bertil Lindblad drove the final nail into the coffin of the “small galaxy” picture of Kapteyn in 1927.**
- **He computed the mass of the Galaxy by counting stars.**
- **He used doppler shifts to compute the relative velocities of GCs to be roughly ≈ 250 km/s.**
- **This speed exceeds the escape speed from the Milky Way Galaxy’s mass according to his star counts**
- **This implies the Galaxy must be much larger than what local star counts indicated**

Bertil Lindblad

The Final Nail

- **Possible Reconciliation:**
  - **Globular clusters escape the Milky Way, but are constantly replenished by new formation mechanisms.**
- **Problems with that:**
  - **Globular clusters are very red.**
  - **Each globular cluster contains roughly 10^5 stars, and the Kapteyn Galaxy doesn’t have enough mass in it to replenish this amount of stars**
- **Even with our contemporary picture of the Milky Way galaxy, the issue of the speed of globular clusters is still with us to some degree.**
- **We think that there is some other mass in the galaxy, that emits no light, but exerts a gravitational force to explain these high velocities.**
  - **This is some of the first evidence for dark matter.**

Modern picture of Milky Way



The Interstellar Medium

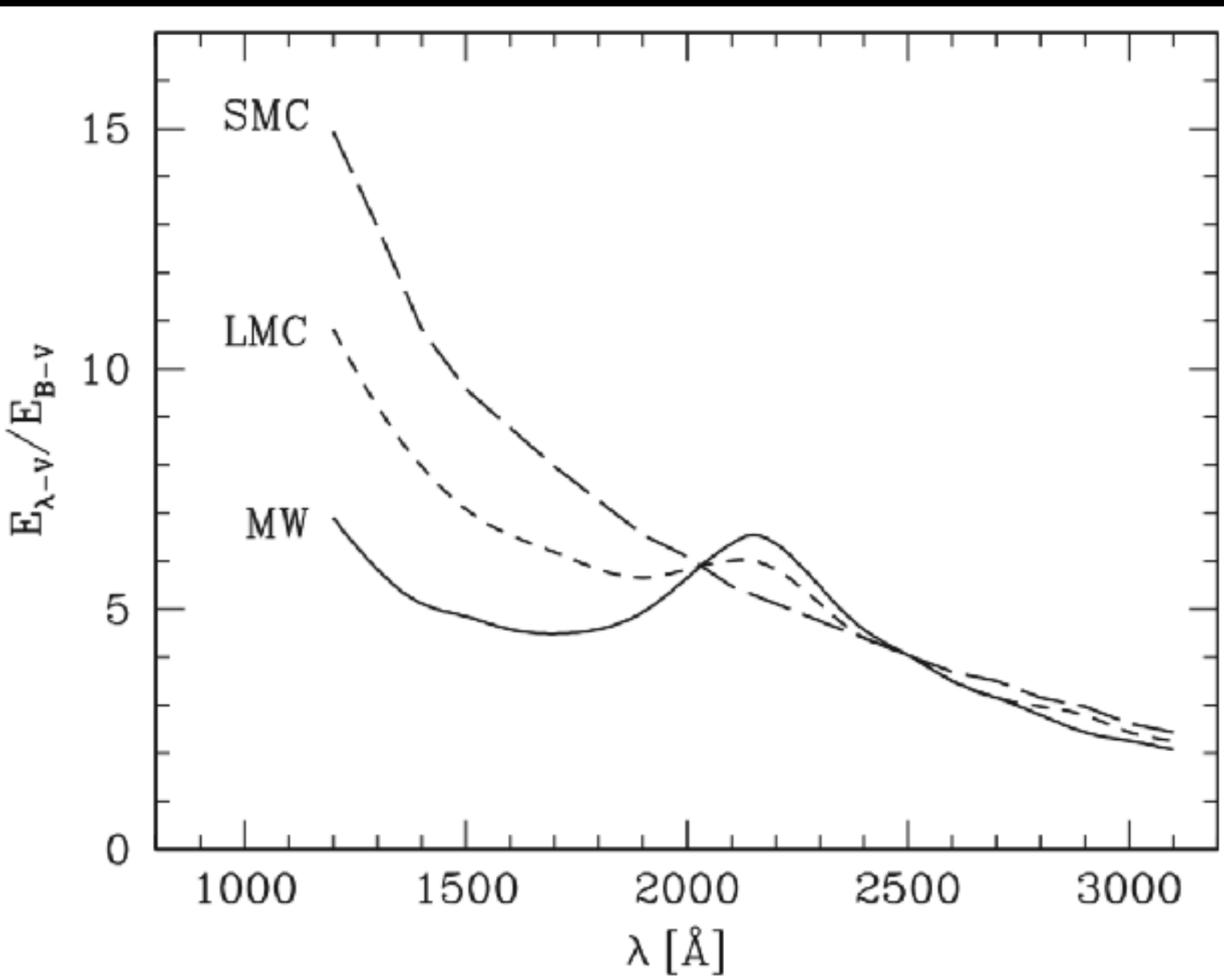
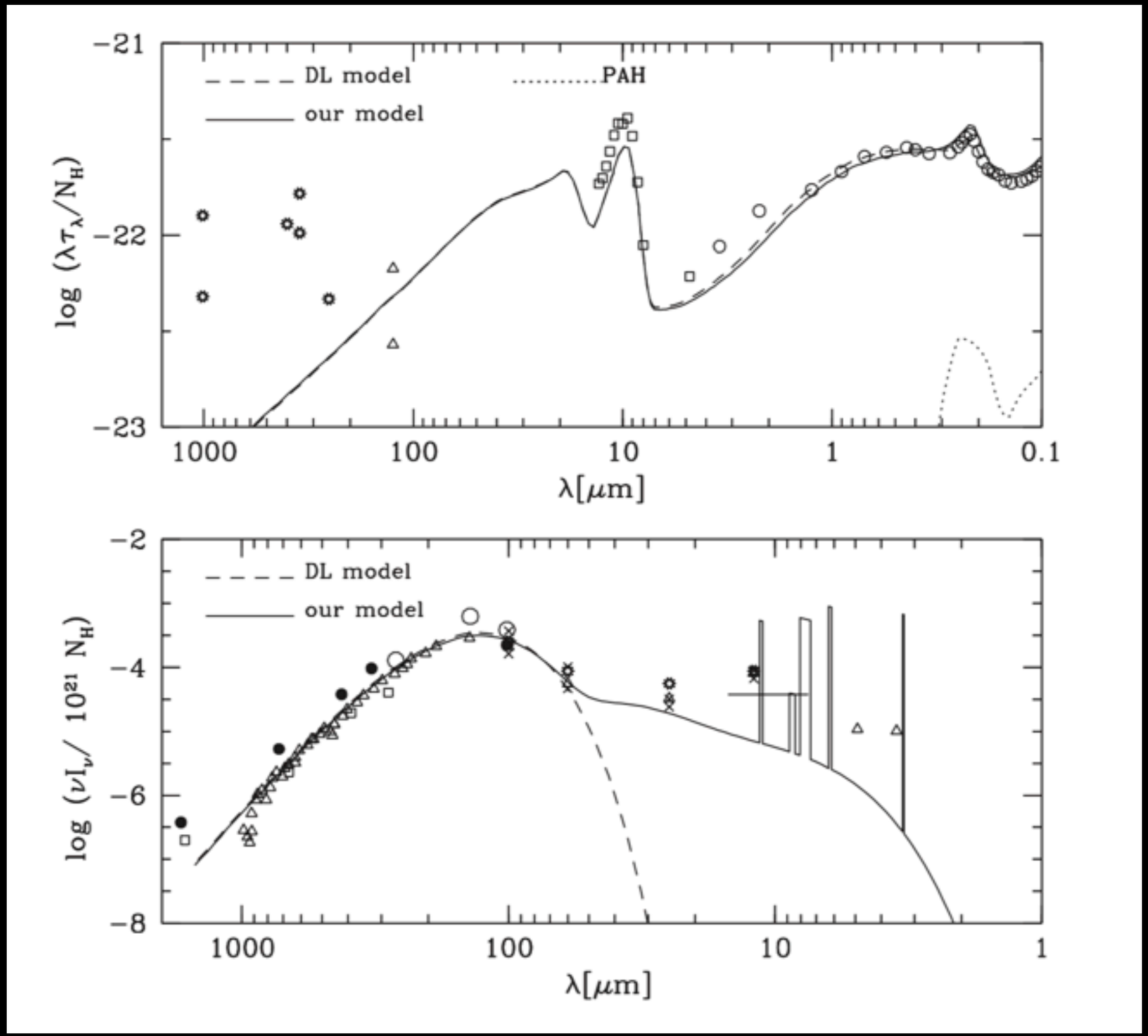


Fig. 10.7. The extinction laws, defined in terms of the ratio of color excesses, for the Milky Way (MW), the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC). These are based on data published in Seaton (1979) and Howarth (1983) in the case of the MW, in Koornneef & Code (1981) in the case of the LMC, and in Bouchet et al. (1985) in the case of the SMC.

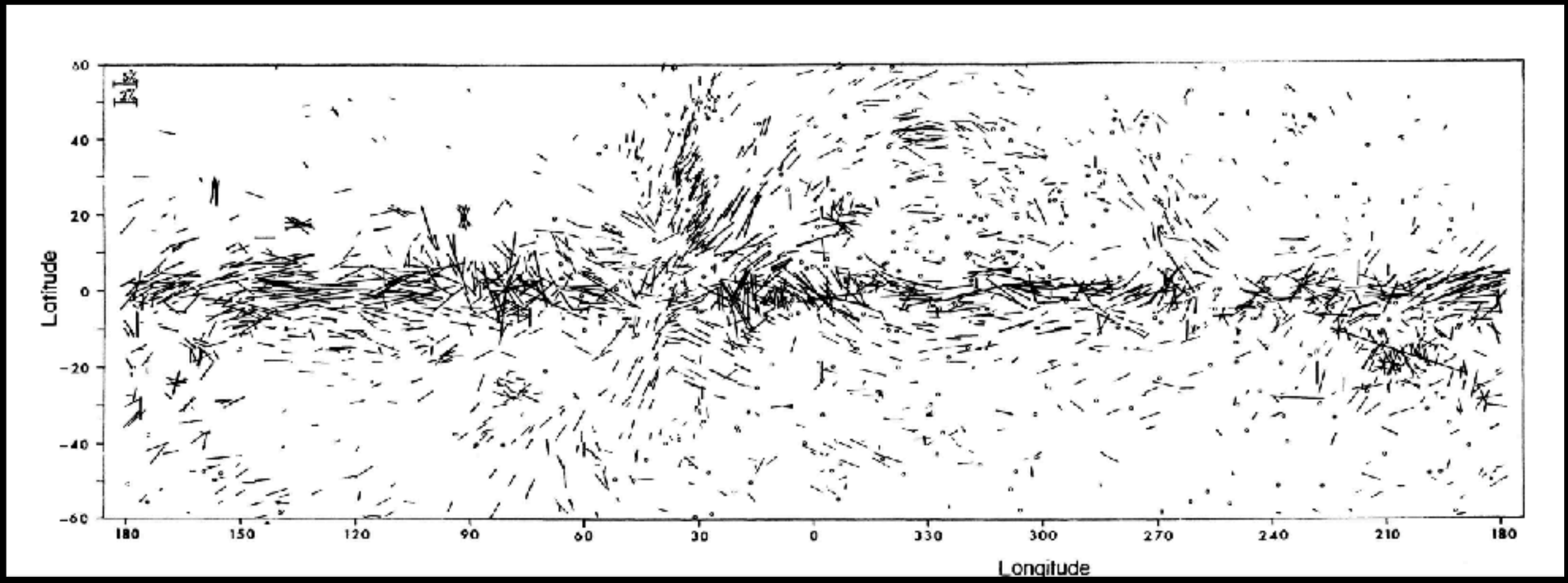
The Interstellar Medium



Dust Extinction

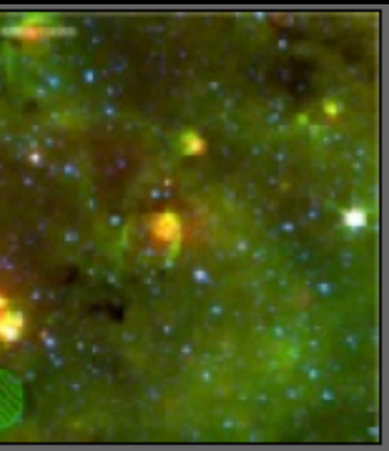
Dust Emission

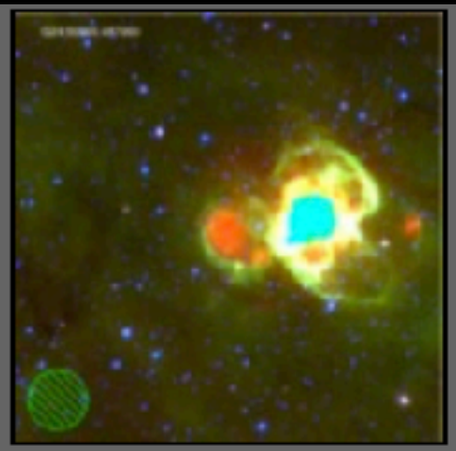
The Interstellar Medium

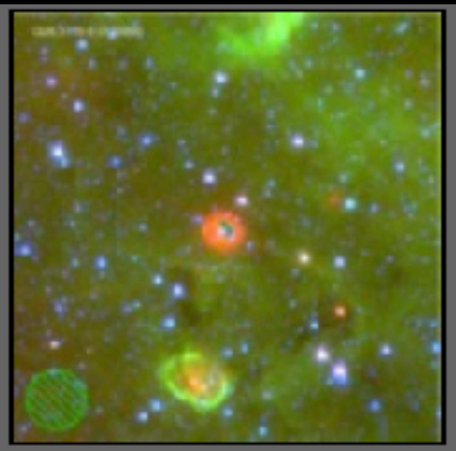


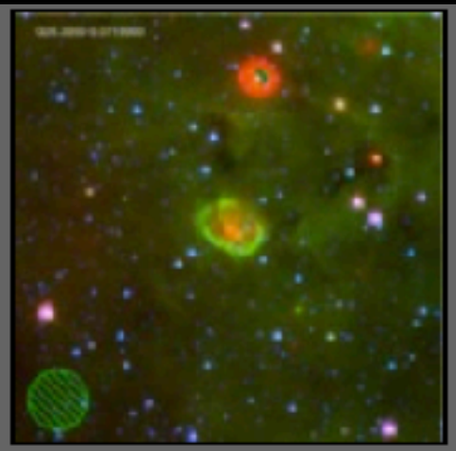
Dust Polarization

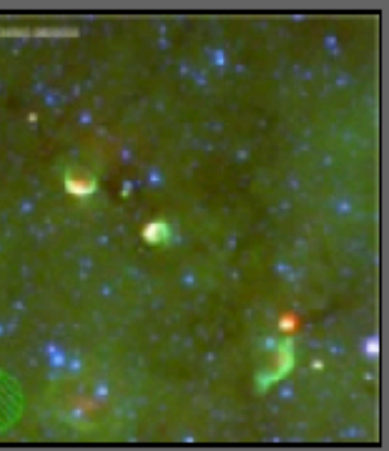
HII regions

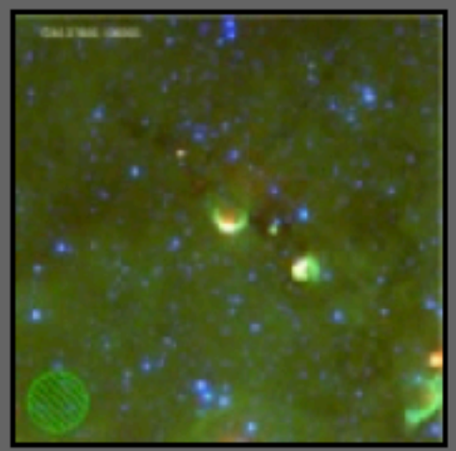


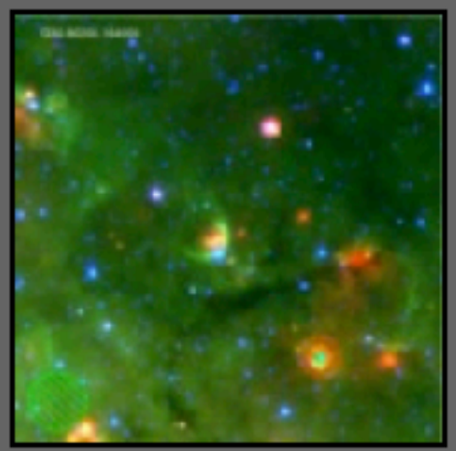


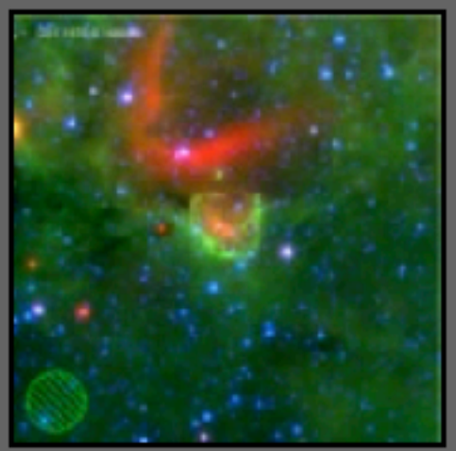


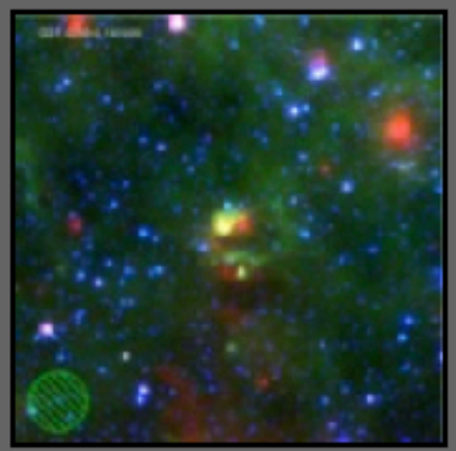


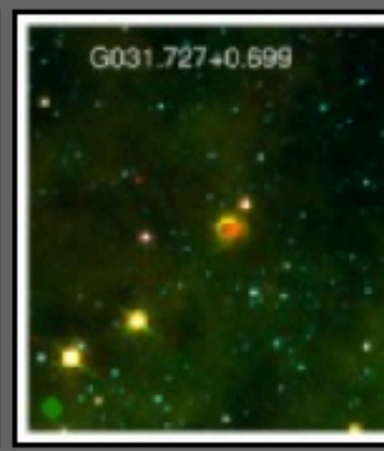


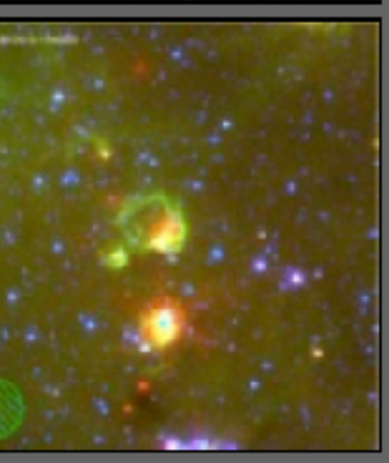


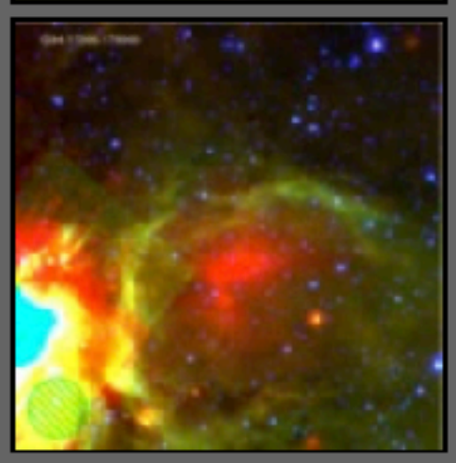


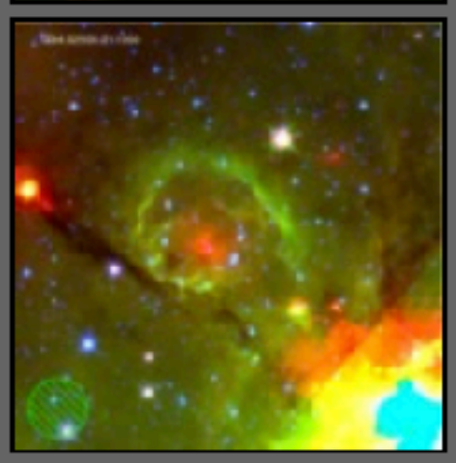


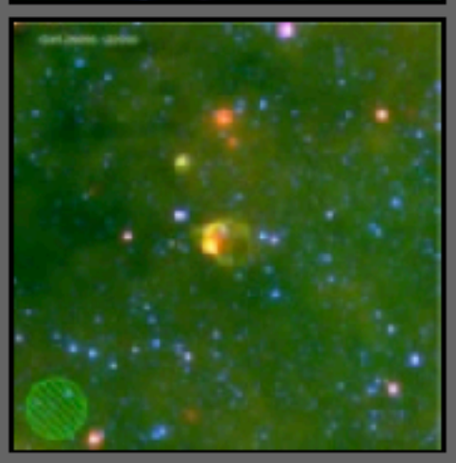


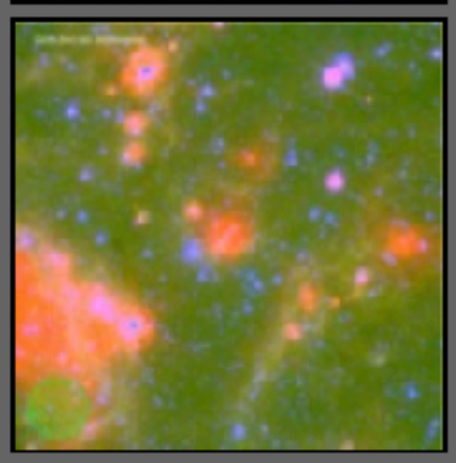


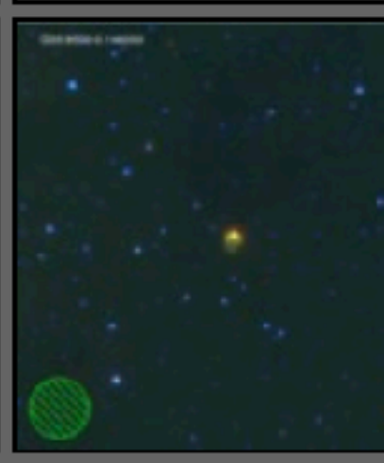


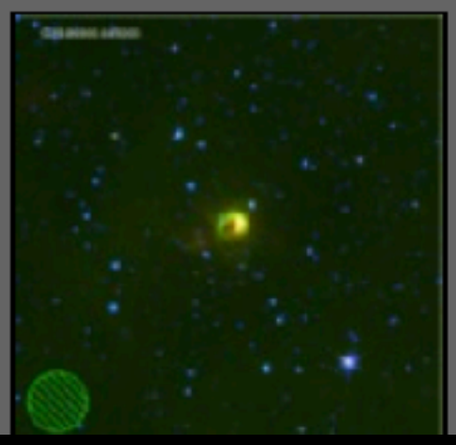


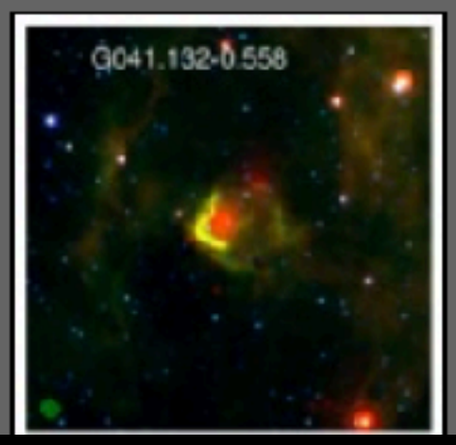


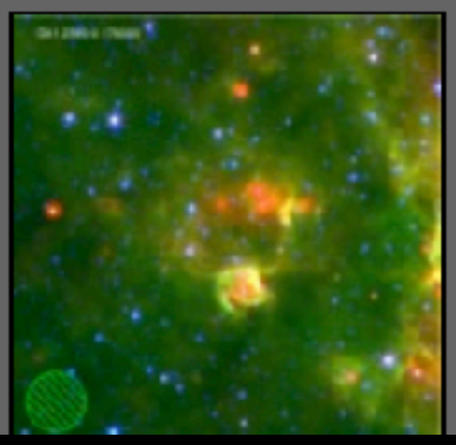


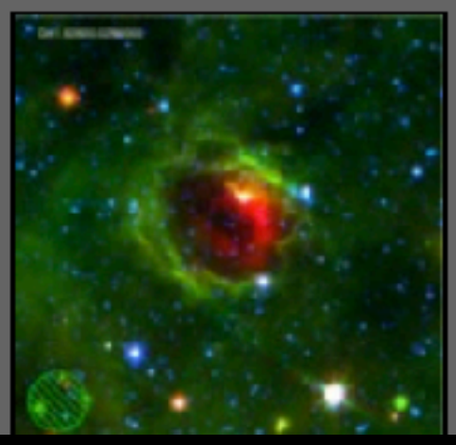


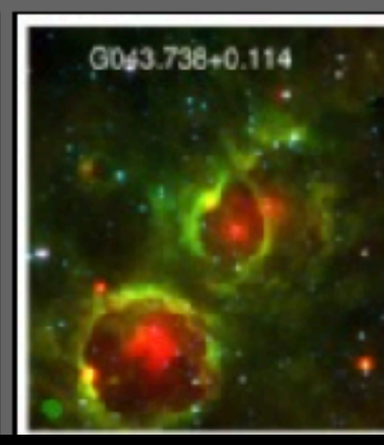


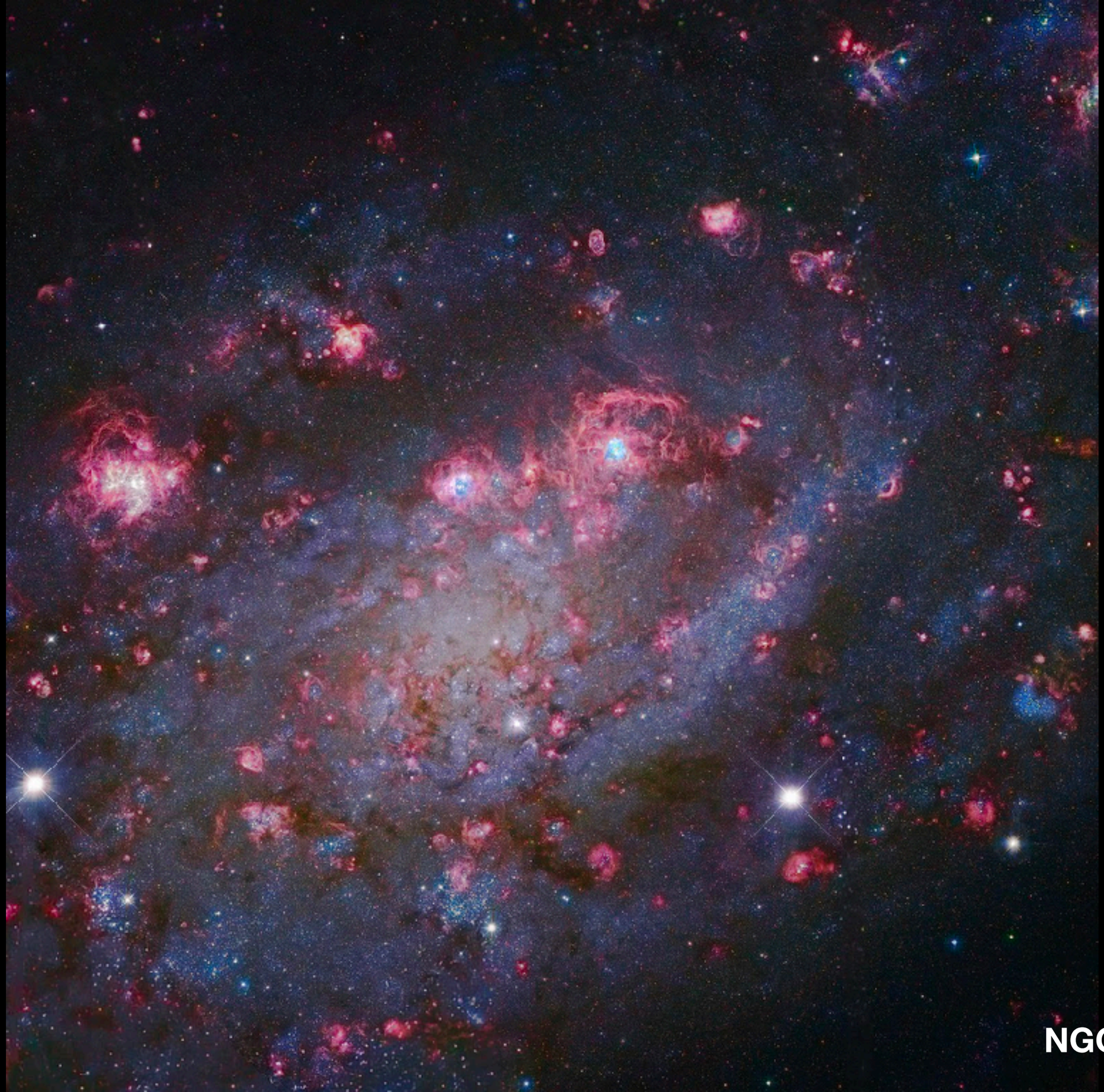




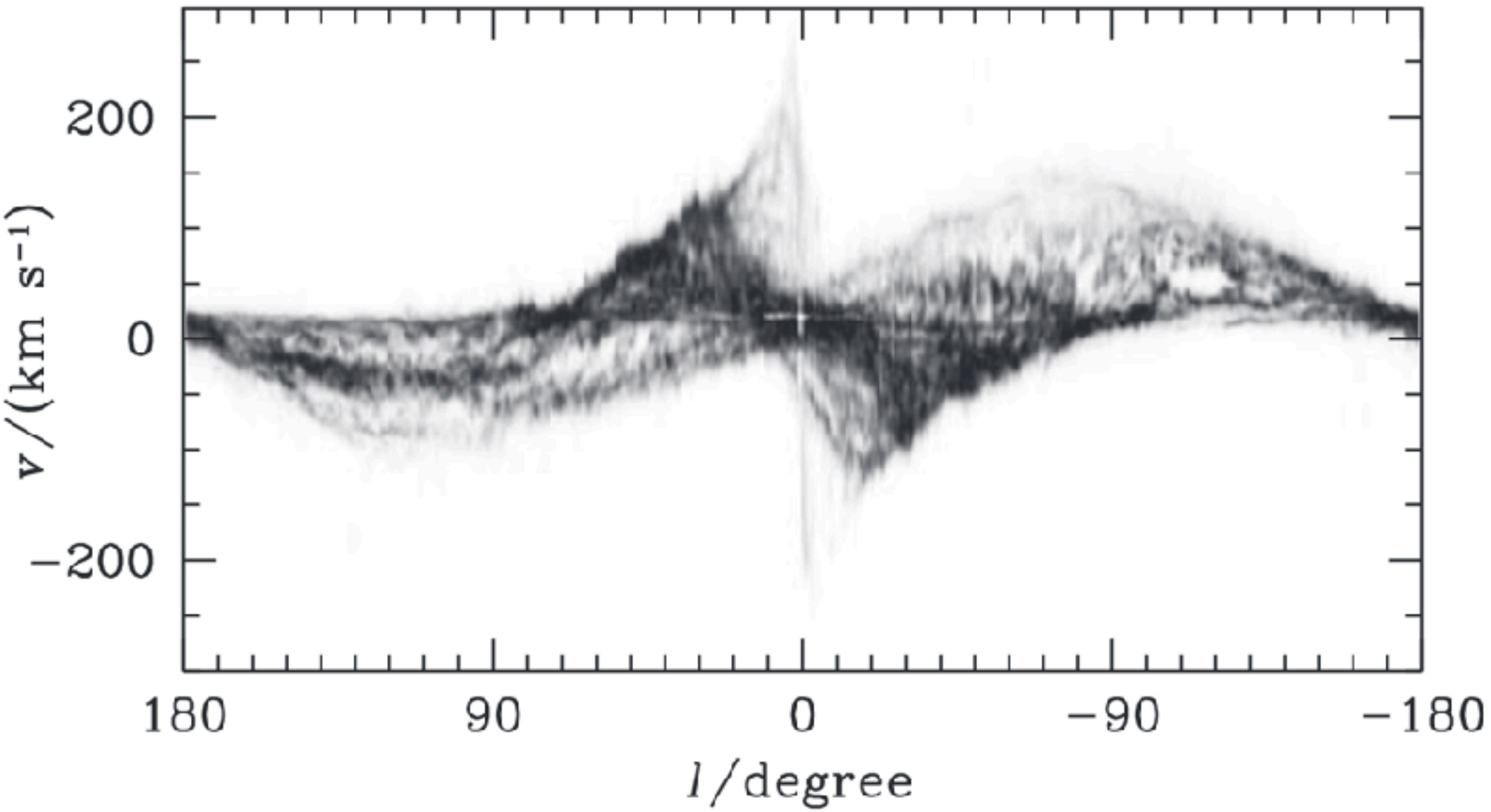




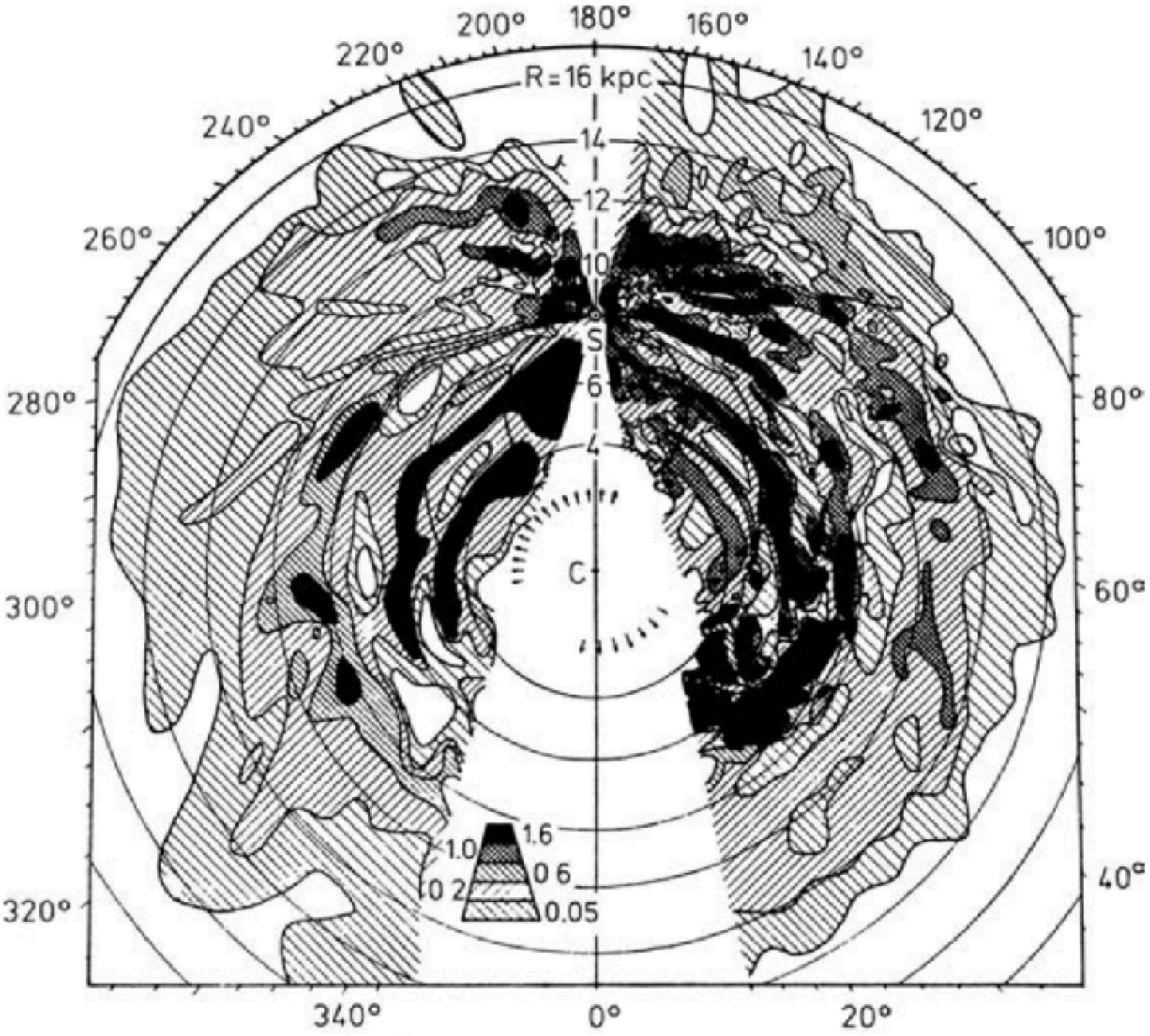



NGC 2403

The Interstellar Medium



Galactic HI (21 cm) emission


200°
180°
160°
220°
140°
R = 16 kpc
240°
120°
14
12
260°
100°
10
S
280°
6
80°
4
C
300°
60°
1.6
1.0
0 6
0 2
0.05
320°
40°
340°
0°
20°